Production of leading charged particles and leading charged-particle jets at small transverse momenta in *pp* collisions at $\sqrt{s} = 8TeV$

CMS Collaboration ; Khachatryan, V ; Sirunyan, A M ; Tumasyan, A ; Aarrestad, T K ; Amsler, C ; Canelli, F ; Chiochia, V ; De Cosa, A ; Hinzmann, A ; Hreus, T ; Kilminster, B ; Lange, C ; Ngadiuba, J ; Pinna, D ; Robmann, P ; Ronga, F J ; Taroni, S ; Yang, Y ; et al

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Production of leading charged particles and leading charged-particle jets at small transverse momenta in *pp* collisions at $\sqrt{s} = 8$ TeV

V. Khachatryan *et al.*[*]
(CMS Collaboration)

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The per-event yield of the highest transverse momentum charged particle and charged-particle jet, integrated above a given $p_{\mathrm{T}}^{\min}$ threshold starting at $p_{\mathrm{T}}^{\min} = 0.8$ and 1 GeV, respectively, is studied in pp collisions at $\sqrt{s} = 8$ TeV. The particles and the jets are measured in the pseudorapidity ranges $|\eta| < 2.4$ and 1.9, respectively. The data are sensitive to the momentum scale at which parton densities saturate in the proton, to multiple partonic interactions, and to other key aspects of the transition between the soft and hard QCD regimes in hadronic collisions.

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I. INTRODUCTION

The production of jets with large transverse momenta $p_{\mathrm{T}} \gg \Lambda_{\mathrm{QCD}} \approx 0.2$ GeV in high-energy proton-proton (pp) collisions originates from the scattering of partons, a process described by perturbative quantum chromodynamics (pQCD), through the convolution of the parton-parton cross section with the density of partons inside the protons. Jet production in pp collisions at the LHC, at transverse momenta $p_{\mathrm{T}} > 20$ GeV and in the pseudorapidity range $|\eta| < 3$, is well described by next-to-leading-order pQCD calculations [1–3]. However, most of the final-state hadrons produced in pp collisions arise from the hadronization of quarks and gluons scattered through "semihard" interactions with exchanged momenta of $\mathcal{O}(1\text{–}3\ \mathrm{GeV})$. At such low values of p_{T}, the theoretical partonic cross section, $d\sigma/dp_{\mathrm{T}}^2 \propto \alpha_S^2(p_{\mathrm{T}})/p_{\mathrm{T}}^4$, where α_S is the strong coupling, becomes very large, and the integrated cross section $\sigma(p_{\mathrm{T}}^{\min}) = \int_{p_{\mathrm{T}}^{\min}} dp_{\mathrm{T}}^2 d\sigma/dp_{\mathrm{T}}^2$ exceeds the total inelastic pp cross section, σ_{inel}. At $\sqrt{s} = 8$ TeV, where $\sigma_{\mathrm{inel}} \approx 70$ mb [4], this occurs at $p_{\mathrm{T}}^{\min}$ values of $\mathcal{O}(3\ \mathrm{GeV})$, much larger than the QCD scale, Λ_{QCD}, at which the strong coupling diverges [5,6].

Model calculations of hadronic collisions often regulate such an infrared divergence through an effective parameter connected to the confinement scale of hadrons [7], such that the leading particle or leading jet production cross sections do not exceed the value of σ_{inel}. Contrary to the inclusive particle or jet production cross sections, the *leading* particle or leading jet production cross sections must indeed approach the total inelastic cross section because only one particle or one jet, the one with highest p_{T} in this case, is considered per event. In addition, at small p_{T}, the parton densities are probed in a region where parton recombination, i.e. saturation (see e.g. Ref. [8]), may occur.

Reference [9] proposes that the jet cross section integrated over $p_{\mathrm{T}} > p_{\mathrm{T}}^{\min}$ can be used as a probe of the transition from the perturbative ($p_{\mathrm{T}}^{\min} \gg \Lambda_{\mathrm{QCD}}$) to the nonperturbative region ($p_{\mathrm{T}}^{\min} \to \Lambda_{\mathrm{QCD}}$). According to Ref. [9], this transition should also be visible for cross sections defined in restricted ranges of pseudorapidity.

The results presented in this paper are based on measurements of single charged particles and jets reconstructed from charged particles alone. The advantage of jets is that they include more particles originating from the outgoing partons, while single charged hadrons carry only a fraction of the parent parton momentum. On the other hand, jets are sensitive to the underlying event (UE) activity, consisting of particles originating from multiple partonic interactions (MPIs) and initial- and final-state radiation, while single leading tracks are not. The measurements based on leading particles and leading jets are therefore complementary. Throughout the text, the term "track jets" refers to detector-level jets, reconstructed from charged-particle tracks observed in the detector, while "charged-particle jets" or just "jets" denotes corrected, stable-particle level jets, consisting of stable charged particles from the final state.

In this paper, the yields, $r(p_{\mathrm{T}}^{\min})$, for pp collisions with a leading charged particle or a leading jet are measured as a function of a minimum transverse momentum, $p_{\mathrm{T}}^{\min}$:

$$r(p_{\mathrm{T}}^{\min}) = \frac{1}{N_{\mathrm{evt}}} \int_{p_{\mathrm{T}}^{\min}} dp_{\mathrm{T}}^{\mathrm{lead}} \left(\frac{dN}{dp_{\mathrm{T}}^{\mathrm{lead}}} \right), \qquad (1)$$

where N_{evt} is the number of selected events with a leading charged particle with $p_{\mathrm{T}} > 0.4$ GeV and $|\eta| < 2.4$ and N is the number of events with a leading charged particle or a leading jet with transverse momentum $p_{\mathrm{T}}^{\mathrm{lead}}$ within $|\eta| < 2.4$ or 1.9, respectively.

[*]Full author list given at the end of the article.

II. PHENOMENOLOGICAL MODELS

The measured distributions are compared to the predictions of different hadronic interaction models of which the tunable parameters (mostly connected to nonperturbative and semihard QCD phenomena) are obtained from comparisons to LHC data such as those on UE activity, inclusive multiparticle production, and diffraction.

The PYTHIA 6 [10] and 8 [11] event generators tame the low-p_{T} behavior of the leading-order pQCD $2 \to 2$ cross sections with a phenomenological factor [5,6] $[\alpha_s^2(p_{\mathrm{T},0}^2 + p_{\mathrm{T}}^2)/\alpha_s^2(p_{\mathrm{T}}^2)][p_{\mathrm{T}}^4/(p_{\mathrm{T},0}^2 + p_{\mathrm{T}}^2)^2]$, where $p_{\mathrm{T},0}$ is a (tunable) infrared regulator that runs with center-of-mass energy. The tunes 4C [12], CUET [13,14], and MONASH [15] are used, featuring different choices of the $p_{\mathrm{T},0}$ cutoff, proton transverse profile, and/or parton distribution functions.

The HERWIG++ [16] Monte Carlo (MC) includes a hard (pQCD $2 \to 2$ interactions) [17] and a soft (nonperturbative) component for multiple interactions [18]. The soft part is parametrized phenomenologically as $d\sigma/dp_{\mathrm{T}}^2 = Ae^{-\beta p_{\mathrm{T}}^2}$. The transition scale between the hard and the soft regions is set by the parameter $p_{\mathrm{T},0}$, obtained from fits to MPI and UE data as well as to the effective cross section for double-parton scatterings. The parameters A and β are fixed by the requirements that the transverse momentum distribution be continuous at the matching scale $p_{\mathrm{T},0}$ and that the model reproduces the measured total cross section. Tune UE-EE-5C [19] is used.

The other two models, QGSJET-II [20] and EPOS [21,22], are based on the Regge–Gribov effective field theory [23], which allows for a consistent treatment of soft and hard scattering processes in terms of the same degrees of freedom (reggeons and pomerons), based on unitarity cuts of the corresponding elastic scattering diagrams. Perturbative parton-parton processes are obtained via “cut (hard) pomeron” diagrams, and multiscattering phenomena (saturation, MPI) are implemented through various procedures [24]. The two models differ in their approximations for the collision configurations (with exact energy sharing imposed in the case of EPOS) and the treatment of diffractive and perturbative contributions (the effective soft-hard transition occurs at $p_{\mathrm{T},0} \sim 1.6$ GeV for QGSJET-II and at $p_{\mathrm{T},0} \sim 2$ GeV for EPOS). Finally, in contrast to other MCs, EPOS includes also collective expansion effects in the final state that boost the final p_{T} distribution of the produced hadrons. It is worth highlighting that, for all MC models, the (center-of-mass energy dependent) $p_{\mathrm{T},0}$ cutoff plays a very similar role to the “saturation scale” (Q_{sat}), which controls the onset of gluon fusion effects in the parton densities [25].

III. EXPERIMENTAL ANALYSIS

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator sampling hadron calorimeter are located within the volume of the solenoid.

The inner silicon tracker measures charged-particle trajectories (“tracks” in the following) within the pseudorapidity range $|\eta| < 2.5$. It provides an impact parameter resolution of about 100 μm and a p_{T} resolution of about 0.7% for 1 GeV tracks at $\eta = 0$ [26]. A more detailed description of the CMS detector, together with definitions of the coordinate system and kinematic variables, can be found in Ref. [27].

The data analyzed in this study were collected during a dedicated proton-proton run with an integrated luminosity of 45 μb^{-1} at a center-of-mass energy of $\sqrt{s} = 8$ TeV. This run has a low instantaneous luminosity and a low probability (~2%) of multiple pp interactions occurring in the same bunch crossing (pileup). Pileup events are rejected by requiring exactly one vertex, following the method described in Ref. [28].

Minimum bias events were selected online with the TOTEM T2 telescopes [29] that are placed symmetrically at about 14 m on both sides from the interaction point (IP). Single tracks are reconstructed in these telescopes with almost 100% efficiency for $p_{\mathrm{T}} > 20$ MeV/c, but because of multiple scattering and the effect of the magnetic field, tracks can be identified as coming from the IP with an efficiency that increases as a function of p_{T} and is greater than 80% for $p_{\mathrm{T}} > 40$ MeV/c [30]. The minimum bias trigger, defined by the requirement of the presence of at least one track candidate in either of the T2 detectors [31], has an efficiency close to 100% [28] for events where a charged particle is produced within the T2 acceptance. According to the PYTHIA 8 and QGSJETII-04 [20] generators, about 91%–96% of the total inelastic cross section at $\sqrt{s} = 8$ TeV is seen by T2 [4], with the uncertainty coming mainly from low mass diffractive events. The present analysis follows the procedure described in Ref. [28], where more details are given on the trigger, data selection, and correction procedures.

Corrections for the contribution of background events triggered by T2 but without a charged primary particle in the T2 acceptance are estimated with simulated events from PYTHIA 8 and EPOS. These models were found to enclose the measured pseudorapidity distributions of charged particles in the forward region [28]. The average corrections for the two models vary from 4% and 1% at $p_{\mathrm{T}}^{\mathrm{min}} \approx 1$ GeV to 7% and 5% at $p_{\mathrm{T}}^{\mathrm{min}} \approx 45$ GeV, for the track and track-jet analysis, respectively. The deviation of PYTHIA 8 and EPOS from the average correction is taken as an estimate of the systematic uncertainty related to the T2 trigger efficiency; it is less than 0.7% for the leading track measurement and varies between 0.1% and 1.0% for the leading track-jet measurement [28].

Events are selected offline by requiring the presence of a leading track in the region $|\eta| < 2.4$ with $p_{\mathrm{T}} > 0.4$ GeV.

These events are used to normalize the integrated distributions in both the leading track and the track-jet measurements. Track-jets are reconstructed offline from tracks with $p_{\mathrm{T}} > 0.1$ GeV and $|\eta| < 2.4$, clustered by using the anti-k_{T} algorithm [32–34] with a distance parameter of 0.5. The track-jet momentum is determined from the sum of all track momenta in the track jet. The pseudorapidity restriction $|\eta^{\mathrm{jet}}| < 1.9$ assures that the track jet is contained within the tracker acceptance.

Detailed MC simulations of the CMS and T2 detectors are based on GEANT4 [35]. Simulated events are processed and reconstructed in the same manner as collision data. For the correction of detector effects, as well as for comparison with models, both the PYTHIA 6 [10] (version 6.426) event generator with tune Z2$*$ [36] and the PYTHIA 8 (version 8.153) generator with tune 4C are used. The final correction is obtained by averaging those from the two generators.

The data are corrected to the stable-particle level, which is defined to include primary charged particles with lifetimes of $c\tau > 1$ cm, either directly produced in the pp collisions or from decays of particles with shorter lifetimes. According to this definition, K_S^0 and Λ hadrons are considered stable. Generated events are selected at the stable-particle level if at least one charged particle with $p_{\mathrm{T}} > 40$ MeV is present within the range $5.3 < |\eta| < 6.5$ and at least one charged particle with $p_{\mathrm{T}} > 0.4$ GeV is found within $|\eta| < 2.4$. In each event, the highest-p_{T} charged particle within $|\eta| < 2.4$ and $p_{\mathrm{T}} > 0.8$ GeV is selected as the leading particle. Charged particles are clustered into jets by using the anti-k_{T} algorithm with a distance parameter of 0.5 with no restriction on p_{T} or η. The leading charged-particle jet is then defined as the charged-particle jet with the highest p_{T} above 1 GeV and $|\eta^{\mathrm{jet}}| < 1.9$.

The average systematic uncertainty in the track reconstruction efficiency is taken to be 3.9% [37]. Its effect is studied by randomly rejecting 3.9% of the tracks and then repeating the analysis. In the jet analysis, for tracks with low p_{T}, the rejection probability is taken as 15% for $p_{\mathrm{T}} < 1$ GeV. However, since the measurement is integrated over p_{T}, it is nearly insensitive to even such large values of the rejection probability. The resulting uncertainty varies between 0.4% and 3.7% for the leading charged-particle analysis and between 2% and 12% for the leading jet analysis. The larger uncertainties correspond to higher $p_{\mathrm{T}}^{\mathrm{min}}$.

The p_{T} distribution of leading track jets is unfolded to the stable-particle level by applying the iterative procedure [38] implemented in ROOUNFOLD [39] in order to correct for the jet reconstruction efficiency and for migrations in jet p_{T}. Thanks to the good p_{T} resolution of the reconstructed tracks, a simple correction for the track-finding efficiency is found to be sufficient for obtaining the p_{T} distribution of leading charged particles. The PYTHIA 6 and PYTHIA 8 MC models are used to generate the response matrices and efficiency corrections, and the average correction from the two generators is used to obtain the p_{T} distributions at the stable-particle level. The corrections vary between 5% and 10% at $p_{\mathrm{T}} \approx 1$ GeV, to 10% and 40% at $p_{\mathrm{T}} \approx 45$ GeV, for the charged particle and the jet measurements, respectively. The deviation from the average is taken as an estimate of the systematic uncertainty related to the correction procedure. This uncertainty varies from 0.6% to 3% for the leading charged-particle analysis, and from 2% to 10% for the leading jet analysis, depending on $p_{\mathrm{T}}^{\mathrm{min}}$.

TABLE I. The systematic uncertainties for the leading charged particle ($0.8 < p_{\mathrm{T}}^{\mathrm{min}} < 50\,\mathrm{GeV}$) and leading jet ($1 < p_{\mathrm{T}}^{\mathrm{min}} < 50\,\mathrm{GeV}$) measurements.

	Uncertainty (%)	
Source	Leading charged particle	Leading jet
T2 trigger efficiency	0.7	0.1–1.0
Tracking efficiency	0.4–3.7	2–12
Correction procedure	0.6–3.0	2.0–10
Total	0.7–4.6	2.5–16

The systematic uncertainties are summarized in Table I.

The per-event yields, defined in Eq. (1), are obtained experimentally as

$$r(p_{\mathrm{T}}^{\mathrm{min}}) = \frac{1}{N_{\mathrm{evt}}} \sum_{p_{\mathrm{T}}^{\mathrm{lead}} > p_{\mathrm{T}}^{\mathrm{min}}} \Delta p_{\mathrm{T}}^{\mathrm{lead}} \left(\frac{\Delta N}{\Delta p_{\mathrm{T}}^{\mathrm{lead}}} \right), \tag{2}$$

where N_{evt} is the number of events with a leading charged particle within $|\eta| < 2.4$ and with $p_{\mathrm{T}} > 0.4$ GeV, $\Delta p_{\mathrm{T}}^{\mathrm{lead}}$ is the bin width, and ΔN is the number of events with a leading charged particle or leading jet in the bin.

IV. RESULTS

Figure 1 shows the integrated distributions for the leading charged particle and leading jet events for $p_{\mathrm{T}}^{\mathrm{min}} >$ 0.8 and 1 GeV, respectively. The distributions fall steeply at large transverse momenta and by construction approach unity at small $p_{\mathrm{T}}^{\mathrm{min}}$. The turnover from a relatively flat to a steeply falling distribution takes place between 1 and 10 GeV. However, the turnover point is different for the leading charged particles and the leading jet measurements. This reflects the fact that when particles are clustered into jets more energy from additional particles is collected within the jet cone. In fact, when the jet cone size is reduced, the leading jet distribution approaches the leading charged-particle distribution.

For the comparison of the data to predictions of QCD MC generators, the latter are rescaled to describe the high-$p_{\mathrm{T}}^{\mathrm{lead}}$ region. This rescaling is applied because the normalization to the total visible cross section, which depends on the low-p_{T} regularization, affects the values of r also at

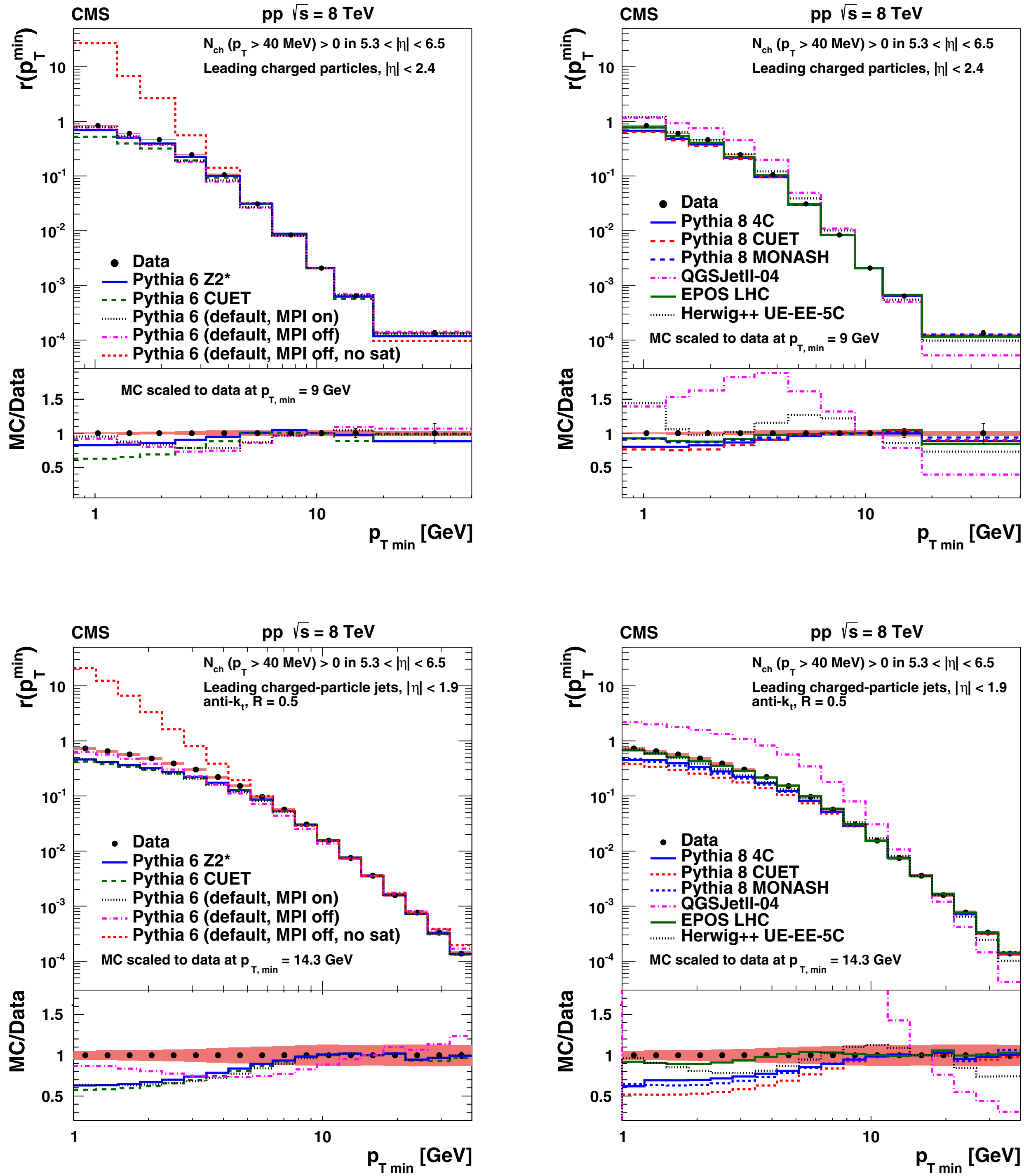

FIG. 1 (color online). The integrated yield, $r(p_{\mathrm{T}}^{\mathrm{min}})$, of events with a leading charged particle within $|\eta| < 2.4$ (top) and with a leading jet within $|\eta| < 1.9$ (bottom), as a function of $p_{\mathrm{T}}^{\mathrm{min}}$. The data are compared to predictions from several PYTHIA 6 tunes (left) and various other event generators (right). The lower panels show the ratios of the MC and the data yields (MC/Data). The error bars indicate the statistical uncertainty, and the red shaded area (only visible in the ratio plots) represents the systematic uncertainty. The predictions are scaled to the measured value of $r(p_{\mathrm{T}}^{\mathrm{lead}} > 9.0\ \mathrm{GeV})$ (top) and $r(p_{\mathrm{T}}^{\mathrm{lead}} > 14.3\ \mathrm{GeV})$ (bottom). The prediction from PYTHIA 6 with MPI off and no parton saturation is not shown in the MC/data ratio plot (left) because of the large disagreement with the data.

high $p_T^{\rm lead}$, where in fact theoretical predictions are more robust and agree better with the data. The exact choice of the normalization point is arbitrary—$r(p_T^{\rm lead} > 9.0\ {\rm GeV})$ for the leading charged particle and $r(p_T^{\rm lead} > 14.3\ {\rm GeV})$ for the leading jet—and the conclusions from this study are drawn from the shape of the distributions alone. The predictions at small $p_T^{\rm lead}$ thus give information on the modelling of the transition region from large to small $p_T^{\rm lead}$.

In Fig. 1 (left plots), the yields $r(p_T^{\rm min})$ as a function of $p_T^{\rm min}$ are compared to the predictions of the event generator PYTHIA 6 with tunes Z2∗ and CUET, as well as with the default version of PYTHIA 6, both with and without MPI. Also shown is the impact of turning off the regularization of the cross section, labeled "PYTHIA 6 (default, MPI off, no sat)." At low $p_T^{\rm min}$, the distribution predicted by this latter model differs by more than 1 order of magnitude from predictions with the regularized cross section.

In Fig. 1 (right plots), the leading charged particle and leading jet data are compared with PYTHIA 8 with tunes 4C, CUET, and MONASH; HERWIG++ (version 2.7.0) with tune UE-EE-5C; EPOS (version 1.99) with LHC tune; and QGSJETII-04.

The leading charged particle and leading jet cross sections are best described by EPOS, which deviates only by up to 10% from the data at very low $p_T^{\rm min}$ and reproduces the data well for $p_T^{\rm min} > 4$ GeV. The event generator HERWIG++ (UE-EE-5C tune) describes the leading jet cross sections fairly well but does not reproduce the transition from large to small p_T in the leading charged-particle cross section. The event generators PYTHIA 6 (Z2∗ and CUET tunes) and PYTHIA 8 (4C, CUET, and MONASH tunes) predict a somewhat different shape for the measured distributions at small p_T.

The comparison of the MC predictions for MPI switched on and off indicates that the effect of MPI is small for leading charged particles, since the particle multiplicity plays only a minor role. However, when clustering particles into jets, the additional particles from MPI play a role, and a large difference is seen when such interactions are switched off in the simulation as in Fig. 1 (bottom left); this brings PYTHIA 6 closer to the data at low $p_T^{\rm min}$.

The predictions with MPI and saturation turned off (dashed curves in Fig. 1, left plots) exhibit a significant deviation from the data at small p_T.

In general, PYTHIA and HERWIG++ describe the trend of the measured distributions but fail to reproduce the details in the $\mathcal{O}(1–5\ {\rm GeV})$ region, which calls for an improvement in their modelling of the transition from the nonperturbative to perturbative regime.

V. SUMMARY

The integrated yields of events with a leading charged particle or a leading charged-particle jet with p_T above a given $p_T^{\rm min}$ threshold, starting at $p_T^{\rm min} = 0.8$ and 1 GeV, respectively, have been measured in pp collisions at $\sqrt{s} = 8$ TeV in a data sample corresponding to an integrated luminosity of 45 $\mu{\rm b}^{-1}$. The particles and jets are measured in the pseudorapidity ranges $|\eta| < 2.4$ and 1.9, respectively.

The yields are found to be relatively flat in the $p_T^{\rm min}$ region around 1 GeV—where the fixed-order perturbative parton-parton cross section diverges in the absence of any mechanism that saturates or unitarizes the pQCD scattering—followed by a steep decrease for $p_T^{\rm min} >$ 10 GeV. The flattening behavior observed at very low $p_T^{\rm min}$ is best described by EPOS, which deviates by at most 10% from the data. The comparison of the data with different phenomenological predictions of hadronic interaction models may help to improve the description of the transition between the perturbative and nonperturbative QCD regimes, which is dominated by the effects of parton density saturation and multiple partonic interactions.

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Grünendahl,[132] O. Gutsche,[132] J. Hanlon,[132] D. Hare,[132] R. M. Harris,[132] J. Hirschauer,[132] B. Hooberman,[132] S. Jindariani,[132] M. Johnson,[132] U. Joshi,[132] B. Klima,[132] B. Kreis,[132] S. Kwan,[132,a] J. Linacre,[132] D. Lincoln,[132] R. Lipton,[132] T. Liu,[132] R. Lopes De Sá,[132] J. Lykken,[132] K. Maeshima,[132] J. M. Marraffino,[132] V. I. Martinez Outschoorn,[132] S. Maruyama,[132] D. Mason,[132] P. McBride,[132] P. Merkel,[132] K. Mishra,[132] S. Mrenna,[132] S. Nahn,[132] C. Newman-Holmes,[132] V. O'Dell,[132] O. Prokofyev,[132] E. Sexton-Kennedy,[132] A. Soha,[132] W. J. Spalding,[132] L. Spiegel,[132] L. Taylor,[132] S. Tkaczyk,[132] N. V. Tran,[132] L. Uplegger,[132] E. W. Vaandering,[132] R. Vidal,[132] A. Whitbeck,[132] J. Whitmore,[132] F. Yang,[132] D. Acosta,[133] P. Avery,[133] P. Bortignon,[133] D. Bourilkov,[133] M. Carver,[133] D. Curry,[133] S. Das,[133] M. De Gruttola,[133] G. P. Di Giovanni,[133] R. D. Field,[133] M. Fisher,[133] I. K. Furic,[133] J. Hugon,[133] J. Konigsberg,[133] A. Korytov,[133] T. Kypreos,[133] J. F. Low,[133] K. Matchev,[133] H. Mei,[133] P. Milenovic,[133,ddd] G. Mitselmakher,[133] L. Muniz,[133] A. Rinkevicius,[133] L. Shchutska,[133] M. Snowball,[133] D. Sperka,[133] J. Yelton,[133] M. Zakaria,[133] S. Hewamanage,[134] S. Linn,[134] P. Markowitz,[134] G. Martinez,[134] J. L. Rodriguez,[134] J. R. Adams,[135] T. Adams,[135] A. Askew,[135] J. Bochenek,[135] B. Diamond,[135] J. Haas,[135] S. Hagopian,[135] V. Hagopian,[135] K. F. Johnson,[135] H. Prosper,[135] V. Veeraraghavan,[135] M. Weinberg,[135] M. M. Baarmand,[136]

M. Hohlmann,[136] H. Kalakhety,[136] F. Yumiceva,[136] M. R. Adams,[137] L. Apanasevich,[137] D. Berry,[137] R. R. Betts,[137] I. Bucinskaite,[137] R. Cavanaugh,[137] O. Evdokimov,[137] L. Gauthier,[137] C. E. Gerber,[137] D. J. Hofman,[137] P. Kurt,[137] C. O'Brien,[137] I. D. Sandoval Gonzalez,[137] C. Silkworth,[137] P. Turner,[137] N. Varelas,[137] B. Bilki,[138,eee] W. Clarida,[138] K. Dilsiz,[138] M. Haytmyradov,[138] V. Khristenko,[138] J.-P. Merlo,[138] H. Mermerkaya,[138,fff] A. Mestvirishvili,[138] A. Moeller,[138] J. Nachtman,[138] H. Ogul,[138] Y. Onel,[138] F. Ozok,[138,xx] A. Penzo,[138] R. Rahmat,[138] S. Sen,[138] P. Tan,[138] E. Tiras,[138] J. Wetzel,[138] K. Yi,[138] I. Anderson,[139] B. A. Barnett,[139] B. Blumenfeld,[139] S. Bolognesi,[139] D. Fehling,[139] A. V. Gritsan,[139] P. Maksimovic,[139] C. Martin,[139] M. Swartz,[139] M. Xiao,[139] P. Baringer,[140] A. Bean,[140] G. Benelli,[140] C. Bruner,[140] J. Gray,[140] R. P. Kenny III,[140] D. Majumder,[140] M. Malek,[140] M. Murray,[140] D. Noonan,[140] S. Sanders,[140] J. Sekaric,[140] R. Stringer,[140] Q. Wang,[140] J. S. Wood,[140] I. Chakaberia,[141] A. Ivanov,[141] K. Kaadze,[141] S. Khalil,[141] M. Makouski,[141] Y. Maravin,[141] L. K. Saini,[141] N. Skhirtladze,[141] I. Svintradze,[141] J. Gronberg,[142] D. Lange,[142] F. Rebassoo,[142] D. Wright,[142] A. Baden,[143] A. Belloni,[143] B. Calvert,[143] S. C. Eno,[143] J. A. Gomez,[143] N. J. Hadley,[143] S. Jabeen,[143] R. G. Kellogg,[143] T. Kolberg,[143] Y. Lu,[143] A. C. Mignerey,[143] K. Pedro,[143] A. Skuja,[143] M. B. Tonjes,[143] S. C. Tonwar,[143] A. Apyan,[144] R. Barbieri,[144] K. Bierwagen,[144] W. Busza,[144] I. A. Cali,[144] L. Di Matteo,[144] G. Gomez Ceballos,[144] M. Goncharov,[144] D. Gulhan,[144] M. Klute,[144] Y. S. Lai,[144] Y.-J. Lee,[144] A. Levin,[144] P. D. Luckey,[144] C. Paus,[144] D. Ralph,[144] C. Roland,[144] G. Roland,[144] G. S. F. Stephans,[144] K. Sumorok,[144] D. Velicanu,[144] J. Veverka,[144] B. Wyslouch,[144] M. Yang,[144] M. Zanetti,[144] V. Zhukova,[144] B. Dahmes,[145] A. Gude,[145] S. C. Kao,[145] K. Klapoetke,[145] Y. Kubota,[145] J. Mans,[145] S. Nourbakhsh,[145] R. Rusack,[145] A. Singovsky,[145] N. Tambe,[145] J. Turkewitz,[145] J. G. Acosta,[146] S. Oliveros,[146] E. Avdeeva,[147] K. Bloom,[147] S. Bose,[147] D. R. Claes,[147] A. Dominguez,[147] R. Gonzalez Suarez,[147] J. Keller,[147] D. Knowlton,[147] I. Kravchenko,[147] J. Lazo-Flores,[147] F. Meier,[147] F. Ratnikov,[147] G. R. Snow,[147] M. Zvada,[147] J. Dolen,[148] A. Godshalk,[148] I. Iashvili,[148] A. Kharchilava,[148] A. Kumar,[148] S. Rappoccio,[148] G. Alverson,[149] E. Barberis,[149] D. Baumgartel,[149] M. Chasco,[149] A. Massironi,[149] D. M. Morse,[149] D. Nash,[149] T. Orimoto,[149] D. Trocino,[149] R.-J. Wang,[149] D. Wood,[149] J. Zhang,[149] K. A. Hahn,[150] A. Kubik,[150] N. Mucia,[150] N. Odell,[150] B. Pollack,[150] A. Pozdnyakov,[150] M. Schmitt,[150] S. Stoynev,[150] K. Sung,[150] M. Velasco,[150] S. Won,[150] A. Brinkerhoff,[151] K. M. Chan,[151] A. Drozdetskiy,[151] M. Hildreth,[151] C. Jessop,[151] D. J. Karmgard,[151] N. Kellams,[151] K. Lannon,[151] S. Lynch,[151] N. Marinelli,[151] Y. Musienko,[151,ee] T. Pearson,[151] M. Planer,[151] R. Ruchti,[151] G. Smith,[151] N. Valls,[151] M. Wayne,[151] M. Wolf,[151] A. Woodard,[151] L. Antonelli,[152] J. Brinson,[152] B. Bylsma,[152] L. S. Durkin,[152] S. Flowers,[152] A. Hart,[152] C. Hill,[152] R. Hughes,[152] K. Kotov,[152] T. Y. Ling,[152] W. Luo,[152] D. Puigh,[152] M. Rodenburg,[152] B. L. Winer,[152] H. Wolfe,[152] H. W. Wulsin,[152] O. Driga,[153] P. Elmer,[153] J. Hardenbrook,[153] P. Hebda,[153] S. A. Koay,[153] P. Lujan,[153] D. Marlow,[153] T. Medvedeva,[153] M. Mooney,[153] J. Olsen,[153] P. Piroué,[153] X. Quan,[153] H. Saka,[153] D. Stickland,[153,c] C. Tully,[153] J. S. Werner,[153] A. Zuranski,[153] E. Brownson,[154] S. Malik,[154] H. Mendez,[154] J. E. Ramirez Vargas,[154] V. E. Barnes,[155] D. Benedetti,[155] D. Bortoletto,[155] L. Gutay,[155] Z. Hu,[155] M. K. Jha,[155] M. Jones,[155] K. Jung,[155] M. Kress,[155] N. Leonardo,[155] D. H. Miller,[155] N. Neumeister,[155] F. Primavera,[155] B. C. Radburn-Smith,[155] X. Shi,[155] I. Shipsey,[155] D. Silvers,[155] A. Svyatkovskiy,[155] F. Wang,[155] W. Xie,[155] L. Xu,[155] J. Zablocki,[155] N. Parashar,[156] J. Stupak,[156] A. Adair,[157] B. Akgun,[157] K. M. Ecklund,[157] F. J. M. Geurts,[157] W. Li,[157] B. Michlin,[157] B. P. Padley,[157] R. Redjimi,[157] J. Roberts,[157] J. Zabel,[157] B. Betchart,[158] A. Bodek,[158] P. de Barbaro,[158] R. Demina,[158] Y. Eshaq,[158] T. Ferbel,[158] M. Galanti,[158] A. Garcia-Bellido,[158] P. Goldenzweig,[158] J. Han,[158] A. Harel,[158] O. Hindrichs,[158] A. Khukhunaishvili,[158] S. Korjenevski,[158] G. Petrillo,[158] M. Verzetti,[158] D. Vishnevskiy,[158] R. Ciesielski,[159] L. Demortier,[159] K. Goulianos,[159] C. Mesropian,[159] S. Arora,[160] A. Barker,[160] J. P. Chou,[160] C. Contreras-Campana,[160] E. Contreras-Campana,[160] D. Duggan,[160] D. Ferencek,[160] Y. Gershtein,[160] R. Gray,[160] E. Halkiadakis,[160] D. Hidas,[160] S. Kaplan,[160] A. Lath,[160] S. Panwalkar,[160] M. Park,[160] S. Salur,[160] S. Schnetzer,[160] D. Sheffield,[160] S. Somalwar,[160] R. Stone,[160] S. Thomas,[160] P. Thomassen,[160] M. Walker,[160] K. Rose,[161] S. Spanier,[161] A. York,[161] O. Bouhali,[162,ggg] A. Castaneda Hernandez,[162] M. Dalchenko,[162] M. De Mattia,[162] S. Dildick,[162] R. Eusebi,[162] W. Flanagan,[162] J. Gilmore,[162] T. Kamon,[162,hhh] V. Khotilovich,[162] V. Krutelyov,[162] R. Montalvo,[162] I. Osipenkov,[162] Y. Pakhotin,[162] R. Patel,[162] A. Perloff,[162] J. Roe,[162] A. Rose,[162] A. Safonov,[162] I. Suarez,[162] A. Tatarinov,[162] K. A. Ulmer,[162] N. Akchurin,[163] C. Cowden,[163] J. Damgov,[163] C. Dragoiu,[163] P. R. Dudero,[163] J. Faulkner,[163] K. Kovitanggoon,[163] S. Kunori,[163] S. W. Lee,[163] T. Libeiro,[163] I. Volobouev,[163] E. Appelt,[164] A. G. Delannoy,[164] S. Greene,[164] A. Gurrola,[164] W. Johns,[164] C. Maguire,[164] Y. Mao,[164] A. Melo,[164] M. Sharma,[164] P. Sheldon,[164] B. Snook,[164] S. Tuo,[164] J. Velkovska,[164] M. W. Arenton,[165] S. Boutle,[165] B. Cox,[165] B. Francis,[165] J. Goodell,[165] R. Hirosky,[165] A. Ledovskoy,[165] H. Li,[165] C. Lin,[165] C. Neu,[165] E. Wolfe,[165] J. Wood,[165] C. Clarke,[166] R. Harr,[166] P. E. Karchin,[166] C. Kottachchi Kankanamge Don,[166] P. Lamichhane,[166] J. Sturdy,[166] D. A. Belknap,[167] D. Carlsmith,[167] M. Cepeda,[167] S. Dasu,[167] L. Dodd,[167] S. Duric,[167] E. Friis,[167] R. Hall-Wilton,[167]

M. Herndon,[167] A. Hervé,[167] P. Klabbers,[167] A. Lanaro,[167] C. Lazaridis,[167] A. Levine,[167] R. Loveless,[167] A. Mohapatra,[167] I. Ojalvo,[167] T. Perry,[167] G. A. Pierro,[167] G. Polese,[167] I. Ross,[167] T. Sarangi,[167] A. Savin,[167] W. H. Smith,[167] D. Taylor,[167] C. Vuosalo,[167] and N. Woods[167]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik der OeAW, Wien, Austria*
[3]*National Centre for Particle and High Energy Physics, Minsk, Belarus*
[4]*Universiteit Antwerpen, Antwerpen, Belgium*
[5]*Vrije Universiteit Brussel, Brussel, Belgium*
[6]*Université Libre de Bruxelles, Bruxelles, Belgium*
[7]*Ghent University, Ghent, Belgium*
[8]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[9]*Université de Mons, Mons, Belgium*
[10]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[11]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[12]*Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil*
[12a]*Universidade Estadual Paulista*
[12b]*Universidade Federal do ABC*
[13]*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*
[14]*University of Sofia, Sofia, Bulgaria*
[15]*Institute of High Energy Physics, Beijing, China*
[16]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[17]*Universidad de Los Andes, Bogota, Colombia*
[18]*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*
[19]*University of Split, Faculty of Science, Split, Croatia*
[20]*Institute Rudjer Boskovic, Zagreb, Croatia*
[21]*University of Cyprus, Nicosia, Cyprus*
[22]*Charles University, Prague, Czech Republic*
[23]*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
[24]*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
[25]*Department of Physics, University of Helsinki, Helsinki, Finland*
[26]*Helsinki Institute of Physics, Helsinki, Finland*
[27]*Lappeenranta University of Technology, Lappeenranta, Finland*
[28]*DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France*
[29]*Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France*
[30]*Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France*
[31]*Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*
[32]*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*
[33]*Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia*
[34]*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
[35]*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
[36]*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
[37]*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
[38]*University of Hamburg, Hamburg, Germany*
[39]*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*
[40]*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*
[41]*University of Athens, Athens, Greece*
[42]*University of Ioánnina, Ioánnina, Greece*
[43]*Wigner Research Centre for Physics, Budapest, Hungary*
[44]*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
[45]*University of Debrecen, Debrecen, Hungary*
[46]*National Institute of Science Education and Research, Bhubaneswar, India*

[47]Panjab University, Chandigarh, India
[48]University of Delhi, Delhi, India
[49]Saha Institute of Nuclear Physics, Kolkata, India
[50]Bhabha Atomic Research Centre, Mumbai, India
[51]Tata Institute of Fundamental Research, Mumbai, India
[52]Indian Institute of Science Education and Research (IISER), Pune, India
[53]Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
[54]University College Dublin, Dublin, Ireland
[55]INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
[55a]INFN Sezione di Bari
[55b]Università di Bari
[55c]Politecnico di Bari
[56]INFN Sezione di Bologna, Università di Bologna, Bologna, Italy
[56a]INFN Sezione di Bologna
[56b]Università di Bologna
[57]INFN Sezione di Catania, Università di Catania, CSFNSM, Catania, Italy
[57a]INFN Sezione di Catania
[57b]Università di Catania
[57c]CSFNSM
[58]INFN Sezione di Firenze, Università di Firenze, Firenze, Italy
[58a]INFN Sezione di Firenze
[58b]Università di Firenze
[59]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[60]INFN Sezione di Genova, Università di Genova, Genova, Italy
[60a]INFN Sezione di Genova
[60b]Università di Genova
[61]INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy
[61a]INFN Sezione di Milano-Bicocca
[61b]Università di Milano-Bicocca
[62]INFN Sezione di Napoli, Università di Napoli 'Federico II', Napoli, Italy, Università della Basilicata, Potenza, Italy, Università G. Marconi, Roma, Italy
[62a]INFN Sezione di Napoli
[62b]Università di Napoli 'Federico II'
[62c]Università della Basilicata
[62d]Università G. Marconi
[63]INFN Sezione di Padova, Università di Padova, Padova, Italy, Università di Trento, Trento, Italy
[63a]INFN Sezione di Padova
[63b]Università di Padova
[63c]Università di Trento
[64]INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
[64a]INFN Sezione di Pavia
[64b]Università di Pavia
[65]INFN Sezione di Perugia, Università di Perugia, Perugia, Italy
[65a]INFN Sezione di Perugia
[65b]Università di Perugia
[66]INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy
[66a]INFN Sezione di Pisa
[66b]Università di Pisa
[66c]Scuola Normale Superiore di Pisa
[67]INFN Sezione di Roma, Università di Roma, Roma, Italy
[67a]INFN Sezione di Roma
[67b]Università di Roma
[68]INFN Sezione di Torino, Università di Torino, Torino, Italy, Università del Piemonte Orientale, Novara, Italy
[68a]INFN Sezione di Torino
[68b]Università di Torino
[68c]Università del Piemonte Orientale
[69]INFN Sezione di Trieste, Università di Trieste, Trieste, Italy
[69a]INFN Sezione di Trieste
[69b]Università di Trieste

[70]Kangwon National University, Chunchon, Korea
[71]Kyungpook National University, Daegu, Korea
[72]Chonbuk National University, Jeonju, Korea
[73]Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
[74]Korea University, Seoul, Korea
[75]Seoul National University, Seoul, Korea
[76]University of Seoul, Seoul, Korea
[77]Sungkyunkwan University, Suwon, Korea
[78]Vilnius University, Vilnius, Lithuania
[79]National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
[80]Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
[81]Universidad Iberoamericana, Mexico City, Mexico
[82]Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
[83]Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
[84]University of Auckland, Auckland, New Zealand
[85]University of Canterbury, Christchurch, New Zealand
[86]National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
[87]National Centre for Nuclear Research, Swierk, Poland
[88]Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
[89]Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
[90]Joint Institute for Nuclear Research, Dubna, Russia
[91]Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
[92]Institute for Nuclear Research, Moscow, Russia
[93]Institute for Theoretical and Experimental Physics, Moscow, Russia
[94]P.N. Lebedev Physical Institute, Moscow, Russia
[95]Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
[96]State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
[97]University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
[98]Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
[99]Universidad Autónoma de Madrid, Madrid, Spain
[100]Universidad de Oviedo, Oviedo, Spain
[101]Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
[102]CERN, European Organization for Nuclear Research, Geneva, Switzerland
[103]Paul Scherrer Institut, Villigen, Switzerland
[104]Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
[105]Universität Zürich, Zurich, Switzerland
[106]National Central University, Chung-Li, Taiwan
[107]National Taiwan University (NTU), Taipei, Taiwan
[108]Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
[109]Cukurova University, Adana, Turkey
[110]Middle East Technical University, Physics Department, Ankara, Turkey
[111]Bogazici University, Istanbul, Turkey
[112]Istanbul Technical University, Istanbul, Turkey
[113]National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
[114]University of Bristol, Bristol, United Kingdom
[115]Rutherford Appleton Laboratory, Didcot, United Kingdom
[116]Imperial College, London, United Kingdom
[117]Brunel University, Uxbridge, United Kingdom
[118]Baylor University, Waco, USA
[119]The University of Alabama, Tuscaloosa, USA
[120]Boston University, Boston, USA
[121]Brown University, Providence, USA
[122]University of California, Davis, Davis, USA
[123]University of California, Los Angeles, USA
[124]University of California, Riverside, Riverside, USA
[125]University of California, San Diego, La Jolla, USA
[126]University of California, Santa Barbara, Santa Barbara, USA
[127]California Institute of Technology, Pasadena, USA
[128]Carnegie Mellon University, Pittsburgh, USA
[129]University of Colorado Boulder, Boulder, USA

[130]Cornell University, Ithaca, USA
[131]Fairfield University, Fairfield, USA
[132]Fermi National Accelerator Laboratory, Batavia, USA
[133]University of Florida, Gainesville, USA
[134]Florida International University, Miami, USA
[135]Florida State University, Tallahassee, USA
[136]Florida Institute of Technology, Melbourne, USA
[137]University of Illinois at Chicago (UIC), Chicago, USA
[138]The University of Iowa, Iowa City, USA
[139]Johns Hopkins University, Baltimore, USA
[140]The University of Kansas, Lawrence, USA
[141]Kansas State University, Manhattan, USA
[142]Lawrence Livermore National Laboratory, Livermore, USA
[143]University of Maryland, College Park, USA
[144]Massachusetts Institute of Technology, Cambridge, USA
[145]University of Minnesota, Minneapolis, USA
[146]University of Mississippi, Oxford, USA
[147]University of Nebraska-Lincoln, Lincoln, USA
[148]State University of New York at Buffalo, Buffalo, USA
[149]Northeastern University, Boston, USA
[150]Northwestern University, Evanston, USA
[151]University of Notre Dame, Notre Dame, USA
[152]The Ohio State University, Columbus, USA
[153]Princeton University, Princeton, USA
[154]University of Puerto Rico, Mayaguez, USA
[155]Purdue University, West Lafayette, USA
[156]Purdue University Calumet, Hammond, USA
[157]Rice University, Houston, USA
[158]University of Rochester, Rochester, USA
[159]The Rockefeller University, New York, USA
[160]Rutgers, The State University of New Jersey, Piscataway, USA
[161]University of Tennessee, Knoxville, USA
[162]Texas A&M University, College Station, USA
[163]Texas Tech University, Lubbock, USA
[164]Vanderbilt University, Nashville, USA
[165]University of Virginia, Charlottesville, USA
[166]Wayne State University, Detroit, USA
[167]University of Wisconsin, Madison, USA

[a]Deceased.
[b]Also at Vienna University of Technology, Vienna, Austria.
[c]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[d]Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.
[e]Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
[f]Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[g]Also at Universidade Estadual de Campinas, Campinas, Brazil.
[h]Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
[i]Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[j]Also at Joint Institute for Nuclear Research, Dubna, Russia.
[k]Also at Suez University, Suez, Egypt.
[l]Also at British University in Egypt, Cairo, Egypt.
[m]Also at Cairo University, Cairo, Egypt.
[n]Also at Fayoum University, El-Fayoum, Egypt.
[o]Also at Université de Haute Alsace, Mulhouse, France.
[p]Also at Brandenburg University of Technology, Cottbus, Germany.
[q]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[r]Also at Eötvös Loránd University, Budapest, Hungary.
[s]Also at University of Debrecen, Debrecen, Hungary.
[t]Also at University of Visva-Bharati, Santiniketan, India.

[u]Also at King Abdulaziz University, Jeddah, Saudi Arabia.
[v]Also at University of Ruhuna, Matara, Sri Lanka.
[w]Also at Isfahan University of Technology, Isfahan, Iran.
[x]Also at University of Tehran, Department of Engineering Science, Tehran, Iran.
[y]Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[z]Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy.
[aa]Also at Università degli Studi di Siena, Siena, Italy.
[bb]Also at Centre National de la Recherche Scientifique (CNRS)—IN2P3, Paris, France.
[cc]Also at Purdue University, West Lafayette, USA.
[dd]Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
[ee]Also at Institute for Nuclear Research, Moscow, Russia.
[ff]Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[gg]Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[hh]Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[ii]Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
[jj]Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[kk]Also at University of Athens, Athens, Greece.
[ll]Also at Paul Scherrer Institut, Villigen, Switzerland.
[mm]Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[nn]Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
[oo]Also at Gaziosmanpasa University, Tokat, Turkey.
[pp]Also at Adiyaman University, Adiyaman, Turkey.
[qq]Also at Mersin University, Mersin, Turkey.
[rr]Also at Cag University, Mersin, Turkey.
[ss]Also at Piri Reis University, Istanbul, Turkey.
[tt]Also at Anadolu University, Eskisehir, Turkey.
[uu]Also at Ozyegin University, Istanbul, Turkey.
[vv]Also at Izmir Institute of Technology, Izmir, Turkey.
[ww]Also at Necmettin Erbakan University, Konya, Turkey.
[xx]Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[yy]Also at Marmara University, Istanbul, Turkey.
[zz]Also at Kafkas University, Kars, Turkey.
[aaa]Also at Yildiz Technical University, Istanbul, Turkey.
[bbb]Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[ccc]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[ddd]Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[eee]Also at Argonne National Laboratory, Argonne, USA.
[fff]Also at Erzincan University, Erzincan, Turkey.
[ggg]Also at Texas A&M University at Qatar, Doha, Qatar.
[hhh]Also at Kyungpook National University, Daegu, Korea.